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Methodology for Flexible Modelling of Escalator Multibody Systems

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ABSTRACT

This paper presents some particular escalator modelling features and methodologies developed to dramatically reduce time cost regarding two aspects: computation and implementation.

CITEF (Railway Technologies Research Centre) has been modelling escalators for three years. During this time, several static, kinematic and dynamic escalator models have been developed and improved. In parallel, automation tools mainly intended for saving time cost have been described in a piecemeal fashion. These tools are based on the repetitiveness of the bodies, and a definition of the joints, forces and loops, and on the cyclic movement of most of the bodies involved. In addition, noise signals have been programmed from MATLAB to simulate them in SIMPACK software in order to apply robust design methods for studying and optimizing certain parameters.

INTRODUCTION

Escalator design has been carried out successfully for more than a century. An exhaustive analysis of patents and viability studies of static, kinematic and dynamic models has been the starting point for developing a methodology to simulate and analyze the overall behavior of this Multibody system from three points of view: static, kinematic and dynamic. All of these kinds of models have produced coherent results. Some representative results have been presented in past papers (Cabanellas et al. 2008a; Cano et al. 2008)

The methodology and models have been developed in parallel form as a feedback system.

STATE OF THE ART

One and a half centuries have passed since the first escalator patent was taken out in 1859, shown in Figure 1. The history of escalators (Cabanellas et al. 2008b; Miravete and Larrode 2007) shows that no drastic change in their basic mechanism and working form has taken place.

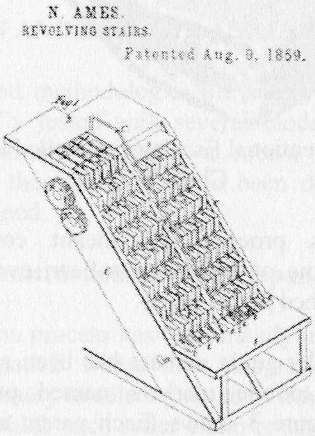

Figure 1: Nathan Ames Revolving Stairs (1859)

Escalator Simulation Models

The number of escalator simulation models developed has been very small so far. When searching for publications in the bibliography related to this field, few papers have been found. LG Industrial Systems (LGIS) has used computer simulation to develop escalators that improve performance over conventional designs using DADS Multibody dynamics software (Sug 1999a).

Despite no other full escalator dynamic simulation models having been found, there are other partial dynamic models related to the study of escalator device handrail systems (Sug 2005) and vibration reduction using robust design (Sug 1999b).

ESCALATOR MODELLING

Mechanically, an escalator is a Multibody system with a considerable number of bodies with their respective joints, contact forces, restrictions, etc. As previously stated herein, there is hardly any bibliography or information on escalator modelling and simulation. CITEF has had to research and select some tools to simulate the static, kinematic and dynamic behavior.

Advanced and complex dynamic models of more than 1000 degrees of freedom have been developed and simulated successfully using SIMPACK (Simulation of Multibody System Package) software. CITEF has had long experience in modelling multibody dynamics behavior using this software. In addition, as conventional escalators are mainly moved using two roller chains linked to each step with a revolute joint, a specific chain modelling SIMPACK module has been used to develop some models. Figure 2 shows a conventional escalator model moved using traction gear wheels. In this model, all chain bodies like chain links, tensioner and traction systems have been modelled by the chain module.

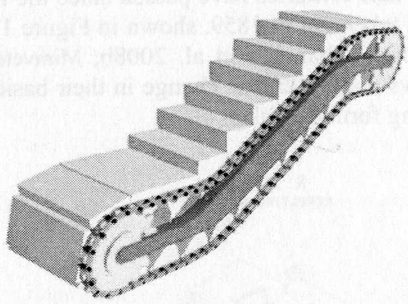

Figure 2: Conventional Escalator modelled using SIMPACK Chain Module

However, this process has meant confronting some difficulties, some of which have been overcome with the methods described in this paper.

For a start, roller-guide contact has been solved as a force between two mobile markers named parent and child markers, as Figure 3 shows. Each parent and child marker has an assigned geometry in which they can move. The child marker is always located at the minimum distance from the parent marker, moving along following its geometry. The contact force has been defined with a spring-damper parallel force element.

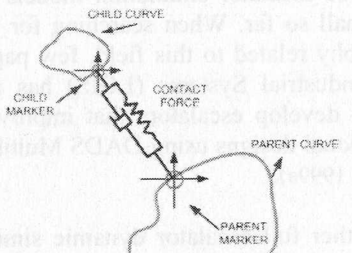

Figure 3: Roller-Guide Contact Force Definition

On the other hand, two types of traction systems have been simulated. A conventional traction system designed using SIMPACK CHAIN module (Cabanellas et al. 2008c), where chain link bodies, their contacts and traction and tensioner system can be created. In addition, linear traction has been simulated using a proportional control system that applies the longitudinal traction force on each chain link in order to maintain its velocity, as the reference velocity curve indicates, during the definite length control.

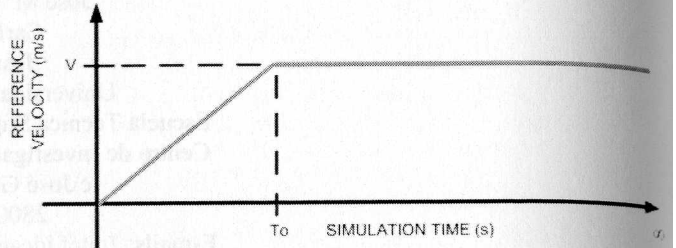

Figure 4: Reference Velocity for Control System

A tensioner system has been created in SIMPACK basic software by doubling the mobile markers and the contact forces existing between them.

In addition, some parameterized programs have been created to facilitate the implementation of some specific guide shapes like pulse-free curves or guides with an inconstant radius, taking into account that these bodies are not made of basic geometries.

Finally, if the time cost is analyzed, there are two clear fronts with a potential high time investment:

1. More than 500 bodies are defined in a model of an escalator with a height of around 4 m. and with a 30º inclined angle.
2. For the most complex models it can take more than a week to simulate a full cycle in some cases. Therefore, time integration is a decisive factor in escalator modelling.

Thus, it is clear that automation in the modelling process is a necessity if greater efficiency is to be obtained. No less important is the time integration, because the main objective of Multibody simulation is to save time and cost compared to research that uses real prototypes to test improvements.

This paper shows how to save integration time and obtain all cycle results in certain cases, under specific hypotheses.

AUTOMATION TOOLS

As we have already described, the simulation of escalator dynamics requires an enormous cost in modelling process and simulation time. CITEF has developed some tools and methodologies in order to reduce both of these drawbacks. The overall dynamic behavior of escalators is dictated by the traction roller chains. These Multibody systems are made up of some repetitive bodies: Chain links (inner and outer), rollers and others auxiliary bodies. In addition, almost all of these bodies have a cyclic movement. Most of the tools developed are based on these characteristics.

Superposition Process

In a permanent regime and with a stationary state, the kinematic and dynamic outputs of each roller or chain link are the same as the previous roller or chain link when they reach the same position. In other words, the values of these outputs are scalar fields because they depend on their position, x and y for instance, for a 2D model. Then, a time variable can be expressed by these spatial variables. This assumption is clear in static and kinematic analysis, however, dynamic simulation adds some oscillations in position and velocity, which have been considered negligible when the hypothesis described can be carried out.

$$F(t) = F(t + nT_c) = G(x, y) \qquad (1)$$

n, number of cycles

T_c, period of a cycle

Therefore, an output variable like velocity along the time of a chain roller, represented in Figure 5, can be associated with its guide geometry.

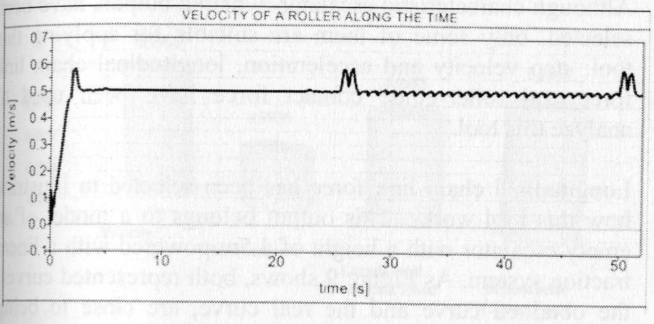

Figure 5: Velocity Output along the Time

By way of illustration, Figure 6 shows the previous velocity output as a scaled offset of the geometry that the corresponding roller has followed. Thus, each colored line length is proportional to velocity values, and all points of the geometry have an associated velocity. Other important dynamic variables such as longitudinal chain link force, roller-guide contact force, step, roller or chain link acceleration, etc., have the same property.

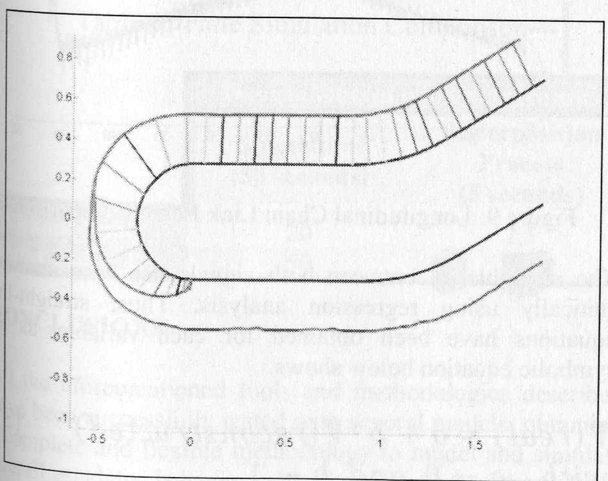

Figure 6: Velocity Polar Diagram

As a result, each output function of any variable related with the bodies which move along the guides could be obtained from the different output functions measured during a time period corresponding to a chain link pitch.

Code Generation

Escalator dynamic model generation involves a hard and heavy task of implementation that supposes a time cost increase. Several MATLAB programs have been created in such a way that there are a lot of bodies, markers, joints, forces, restrictions, etc, with similar functions and definition.

These programs developed produce and export to a separate text document the corresponding code that has been used in SIMPACK files to define each repetitive feature of the model. Therefore, the number of chain links in the roller chain of the model is irrelevant.

On the other hand, full SIMPACK files have been generated from MATLAB software in order to define some parameterized geometries, like guide geometries, single input functions and input functions arrays. These files are fully legible by SIMPACK software.

Input functions are temporary functions that can be used to define a lot of SIMPACK variables. Thus, some applied states have been reproduced (empty or full escalator, an escalator becoming full, etc). One of the advantages of using this implementation method is that any programmable function in MATLAB can be used in SIMPACK simulations.

SIMULATION AND RESULTS ANALYSIS

All the tools and methodologies previously described have been successfully tested with several models for reducing time integration and to make a robust analysis. Some applications of the tools that have been described in this paper are explained.

Incremental Construction of Time Responses

The superposition process has been mainly used in advanced and complex models where time integration is a critical factor. It is necessary to select a range of time corresponding to the time in which each roller chain reaches the next one. Although the starting time point could be any, for example, second 23, as the following figures show, the less the initial time, the greater the time cost reduction.

Figure 7 shows the absolute linear velocity output of a dynamic escalator model simulated in SIMPACK. This model is characterized by chain links of 0.405 m, a reference absolute linear velocity of 0.5 m/s and linear traction system located at the upper part of the right inclined zone. All bodies have been modelled as rigid bodies and friction force has not been taken into account. In addition, the case simulated is an "empty escalator".

Four rollers, called sequentially, have been selected in order to exemplify how the superposition tool works. From starting time, a range of 0.81 seconds has been plotted for all rollers. The lower plot shows the continuous simulation of the first roller, checking stretch by stretch the coherence between both reconstructed and continuous signals.

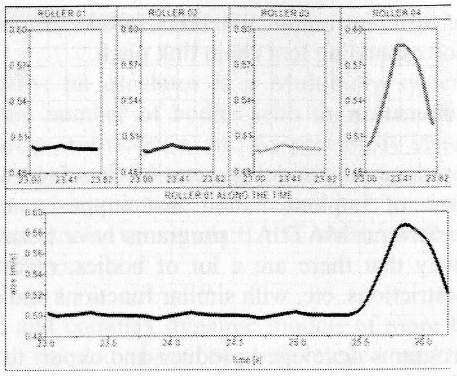

Figure 7: Dynamic Absolute Linear Velocity Superposition

Hereafter, the efficiency and consistency of this tool will be statistically quantified for some different outputs of this model by correlation coefficient.

Robust Design

Taguchi Methods (Wu 1997) have been applied to study the most robust tensioner parameters design that minimizes velocity standard deviation. The tensioner system is defined by three parameters: damping, stiffness and pre-load force. Three levels have been selected for each parameter. The equation below shows the formula used to calculate the signal-to-noise ratio by applying the minimization criterion.

$$S/_R = -10 \cdot Log_{10}\left[\frac{1}{n}\sum_{i=1}^{i=n} Y_i^2\right] \qquad (2)$$

The noise signal is made up of random loads that represent the weight of passengers distributed by a statistical probability distribution with a mean and a pre-selected standard deviation. In addition, the probability of a passenger going up on the escalator is 50%. A code generation tool has been used to create the input functions arrays that define one noise signal for each step, for any number of cycles, chain link pitch or number of steps. All of these characteristics are parameterized in MATLAB code.

As an example, Figure 8 shows five noise signals of five consecutive steps for 20 cycles of an escalator with 60 steps, a distance between step roller of 0.405 m and a reference velocity of 0.5 m/s. The probability distribution used is a uniform distribution with a mean of 97 kg and a standard deviation of 5.625 kg.

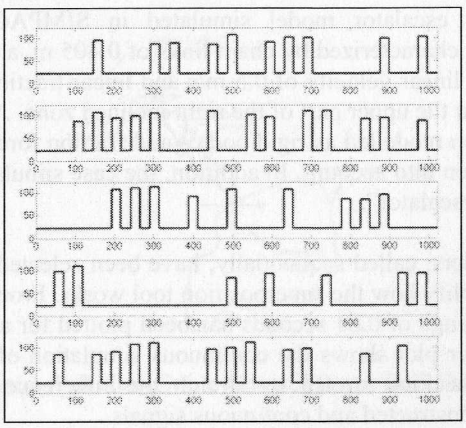

Figure 8: Noise Signal Example

This technique could be used to optimize any other parameter in a robust way, saving the costs of real experiments that involve a prototype construction.

DISCUSSION

Different outputs related to bodies that are moving in a closed curve have been generated using this superposition process. Thus, static, kinematic and dynamic outputs along a cycle have been reconstructed. The most critical reconstruction is the dynamic one, so, this paragraph is dedicated to analyzing the coherence between real and reconstructed signals.

Dynamic reconstruction requires simulating for around 5 seconds. Theoretically, less than a second would be enough; however, there is a transitory regime at the beginning and constant velocity is reached after a few seconds, depending on how the reference velocity for the control system is defined.

Although characteristic escalator dynamic outputs have been selected, only some of them are suitable for applying this tool: step velocity and acceleration, longitudinal chain link force and roller-guide contact force have been used to analyze this tool.

Longitudinal chain link force has been selected to illustrate how this tool works. This output belongs to a model of an empty escalator with a height of 4.5m powered with a linear traction system. As Figure 9 shows, both represented curves, the obtained curve and the real curve, are close to being superposed. The Real Curve has been obtained by a cycle of simulation, in order to compare with the curve created through the superposition process.

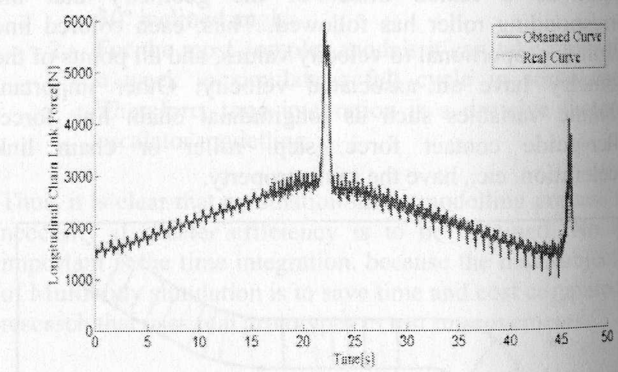

Figure 9: Longitudinal Chain Link Force Comparison

The resemblance between both signals has been analyzed statically using regression analysis. Thus, straight-line equations have been obtained for each variable, as the symbolic equation below shows.

$$V(real) = a + b \cdot V(reconstructed) \qquad (3)$$
$$with \quad a \rightarrow 0 \ and \ b \rightarrow 1$$

The Observed-Predicted graphic is shown in Figure 10, distinguishing a clear straight line that divides the first quadrant, which means the independent parameter of equation (3) tends to be null and the other tends to the unity.

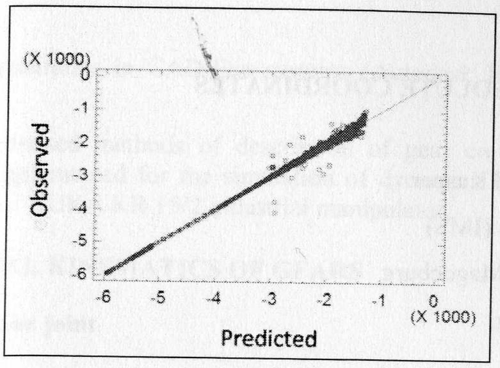

Figure 10: Observed-Predicted Relation for Longitudinal Chain Link Force Output

The rest of the reconstructed outputs present similar statistical results to the example described in this work. The working form of this tool has been evaluated by correlation coefficients, represented in Figure 11 as a bar diagram.

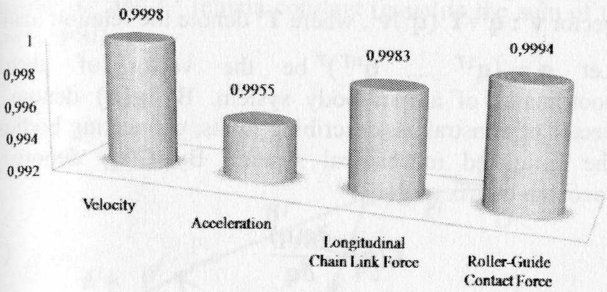

Figure 11: Correlation Coefficients

As the minimum correlation coefficient exceeds 0.99, this tool presents an efficient, accurate, consistent and powerful method for reconstructing any signal under the assumptions previously detailed. Thus, time integration cost is dramatically reduced. As Table 1 shows, the time cost reduction can reach 90% in relative terms for a full load case, and a range of 18 to 45 days per full cycle simulation.

Table 1: Time Simulation Comparison

	Days to Obtain one Cycle Results	
	Simulation (50 seconds)	Superposition Process (5 seconds)
Without Load	20	2,5
Full Load	50	[illegible]

CONCLUSIONS

All the aforementioned tools and methodologies described have been successfully tested with several models, obtaining a complete and flexible methodology to model and simulate overall escalator behavior, reducing time cost and resolving some modelling problems.

CITEF is developing and implementing new concepts in escalators, a product that has become stagnant or constant since its conception. Some lines of research are being followed by CITEF with simulation software always being the option for testing and analyzing any conventional or innovative model.

Furthermore, CITEF is working to develop a full design cycle methodology in the escalator field that will be completed with a dynamic model experimental validation.

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